Waveguide Fiber for Dispersion and Slope Compensation

This application claims the benefit of and priority to U.S. Provisional Patent Application Number 60/271,754, filed February 26, 2001.

Background of the Invention

1. Field of the Invention

The present invention relates generally to an optical waveguide fiber for dispersion compensation, and particularly to such a waveguide fiber that compensates dispersion and dispersion slope in a high performance optical fiber system.

2. Technical Background

Large effective area optical waveguide fibers have played a key role in enabling long distance, high data rate, wavelength division multiplexed systems. Data rates in the range of 40 GB/s over each of about forty channels have already been reached in commercial systems and even higher rates and channel counts are in the planning stage. Dispersion compensation is a protocol that was adopted early in the design of single channel high performance systems. To augment the beneficial effects of dispersion compensation for multi-channel wavelength division multiplexed systems, effectively extending the dispersion compensation over an extended operating wavelength band, the concept of dispersion slope compensation was introduced.

At present, the combination of improved transmitters and receivers, large effective area waveguide fibers, and dispersion and dispersion slope compensating fibers has increased fiber span length between electronic regeneration modules in high performance systems into the range of hundreds of kilometers.

Improvement in the properties of the compensating optical waveguide fibers can further increase span length between regenerators to decrease cost and at the same time enable even higher data rates. By means of such improvement, existing systems can be upgraded in terms of data rate, the data network can be expanded to reach a wider customer base, and the next generation of telecommunications systems can become a reality.

There is therefore a need for a dispersion and dispersion slope compensating optical waveguide fiber that has sufficiently high negative dispersion to decrease compensating waveguide fiber length, relatively low attenuation, and a ratio of total dispersion to total dispersion slope essentially equal to that of the new large effective area waveguide fibers.

Definitions

The following definitions are in accord with common usage in the art.

- The refractive index profile is the relationship between refractive index or relative refractive index and waveguide fiber radius.
- A segmented core is one that is divided into at least a first and a second waveguide fiber core portion or segment. Each portion or segment is located along a particular radial length, is substantially symmetric about the waveguide fiber centerline, and has an associated refractive index profile.
- The radii of the segments of the core are defined in terms of the respective refractive indexes at respective beginning and end points of the segments. The definitions of the radii used herein are set forth in the figures and the discussion thereof.
- The effective area is

$A_{eff} = 2\pi (\int E^2 r\, dr)^2/(\int E^4 r\, dr)$, where the integration limits are 0 to ∞, and E is the electric field associated with light propagated in the waveguide.

- The relative refractive index percent, $\Delta\% = 100 \times (n_i^2 - n_c^2)/2n_i^2$, where n_i is the maximum refractive index in region i, unless otherwise specified, and n_c is the average refractive index of the cladding region, which in this application is taken to the refractive index of silica, SiO_2.

- The bend resistance of a waveguide fiber is expressed as induced attenuation under prescribed bending conditions. A bend test referenced herein is the pin array bend test that is used to compare relative resistance of waveguide fiber to bending. To perform this test, attenuation is measured for a waveguide fiber with essentially no induced bending loss. The waveguide fiber is then woven in a serpentine path through the pin array and attenuation again measured. The additional attenuation induced by bending is the difference between the two measured attenuation values. The pin array is a set of ten cylindrical pins arranged in a single row and held in a fixed vertical position on a flat surface. The pin spacing is 5 mm, center to center. The pin diameter is 0.67 mm. During testing, sufficient tension is applied to make the serpentine woven waveguide fiber conform to the portions of the pin surface at which there is contact between fiber and pin.

- Total dispersion is the sum of material dispersion and waveguide dispersion present in an optical waveguide fiber.

- End to end dispersion of a span of optical waveguide fibers is the amount of dispersion of a pulse traversing the length of the span. Mathematically, the end to end dispersion can be expressed as, $\sum_i l_i D_i$, where, l_i is the length of waveguide fiber having a total dispersion D_i. The sum of all the lengths l_i is the span length.

Summary of the Invention

One aspect of the present invention is a total dispersion and total dispersion slope compensating optical waveguide fiber having a segmented core region. The core includes a central segment surrounded by a first and a second annular segment. The central segment has relative index percent $\Delta_1\%$

greater than 1.4% and a radius less than 3 μm. The first annular segment has relative index Δ_2% more negative than -0.3%, and radius r_2 greater than 6 μm. The second annular segment has relative index Δ_3% greater than 0.15%, and radius r_3 greater than 9 μm. These segment parameters are chosen such that Δ_1% is greater than Δ_3%, r_3 is greater than r_2, and, the combination of Δ_i%'s and r_i's provide a negative total dispersion slope and a ratio of total dispersion to total dispersion slope in the range of 40 nm to 60 nm at a wavelength of 1550 nm.

In a particular embodiment of the segmented core in accord with the invention: $1.4\% \leq \Delta_1\% \leq 2\%$, $1.5\ \mu m \leq r_1 \leq 3.0\ \mu m$; $-0.3\% \leq \Delta_2\% \leq -0.45\%$, $6.0\ \mu m \leq r_2 \leq 8.0\ \mu m$; and, $0.15\% \leq \Delta_3\% \leq 0.85\%$, $9\ \mu m \leq r_3 \leq 12.0\ \mu m$. A preferred range of Δ_1% is from 1.4 % to 1.8%. The attenuation of an optical waveguide fiber made in accord with the invention has attenuation at 1550 nm less than 0.60 dB/km and total dispersion slope at 1550 nm more negative than -1.5 ps/nm^2-km.

In a further embodiment of the invention in accord with this first aspect, the clad layer is divided into a first and a second layer. The first layer is nearer the core region and has a relative refractive index percent Δ_{c1}% less than Δ_{c2}%, the relative index of the second clad. The radius r_{1c} of the first clad layer is greater than 22 μm. The difference in relative index percent of the second clad layer compared to that of the first clad layer is less than or equal to 0.1%. This difference can be achieved by using an index decreasing dopant in the first clad layer or an index increasing dopant in the second clad layer. As an alternative, both clad layers may be doped to achieve the desired refractive index difference.

Another embodiment in accord with the first aspect of the invention r_{1c} has a range from 25 μm to 35 μm and the difference between Δ_{c1}% and Δ_{c2}% has a range from 0.05% to 0.08%. In this embodiment, the radii and relative refractive index percents can be chosen to provide cut off wavelength, which includes cut off of both the LP_{11} and the LP_{02} modes (as is known in the art, cut off includes those configurations wherein the particular mode may be propagated, but is so highly attenuated that it is cut off for practical purposes),

zero dispersion wavelength less than or equal to 1525 nm, attenuation at 1550 nm less than 0.60 dB/km, and dispersion slope at 1550 nm more negative than -1.5 ps/nm^2-km. Cut off wavelength in this application is the wavelength at or above which both the LP_{11} and the LP_{02} modes are not propagated (or are so highly attenuated that for practical purposes the modes are not propagated) in the optical waveguide fiber. The cut off wavelength refers to the fiber in a cabled configuration unless otherwise specified.

In another aspect, the present invention includes an optical waveguide fiber span that is compensated for total dispersion and total dispersion slope. The span includes a first optical waveguide fiber having a length L_1 and, at 1550 nm, a positive total dispersion and total dispersion slope and a second optical waveguide fiber having a length L_2 and, at 1550 nm, a negative total dispersion and total dispersion slope. In order for the two lengths to provide a compensated span, the ratio of total dispersion to dispersion slope for each of the waveguide fiber lengths should be equal or nearly equal. The ratios may differ by 5% at 1550 nm and still provide adequate compensation over the 1550 nm wavelength window, which usually extends from 1525 nm to 1575 nm. In the ideal case the ratios are equal so that compensation is equal across the operating wavelength window. However, if the ratios differ by 5%, a length of the compensating fiber can be chosen to completely compensate dispersion at a wavelength at the center of the operating window. Compensation at wavelengths +/-25 nm from the center wavelength can still be within about 2 % of complete compensation.

A sample calculation illustrating this point is given below. It will be understood that the tolerance choice of 5% is appropriate for high performance systems. Other choices of tolerance can be made based upon the design criteria of a particular system. For example, if the wavelength window of operation is only 10 nm, a much higher tolerance on the ratio is allowable.

Because the attenuation of the compensating fiber in accord with the invention is typically higher than that of the fiber to be compensated, the length L_2 of the compensating fiber is advantageously small compared to the length L_1 of the compensated fiber. In particular the ratio L_1/L_2 is not less than 35. By

proper choice of the lengths L_1 and L_2, essentially any end to end dispersion for the span can be achieved. A choice of zero end to end dispersion is desired in most systems. However, while end to end dispersion can be chosen to be zero, the local total dispersion along the span can be non-zero. For example, the local total dispersion along the fiber can be greater than or equal to 1.0 ps/nm-km at 1550 nm, an amount of total dispersion sufficient to effectively prevent non-linear dispersion due to four wave mixing.

Additional features and advantages of the invention will be set forth in the detailed description which follows, and in part will be readily apparent to those skilled in the art from that description or recognized by practicing the invention as described herein, including the detailed description which follows, the claims, as well as the appended drawings.

It is to be understood that both the foregoing general description and the following detailed description are merely exemplary of the invention, and are intended to provide an overview or framework for understanding the nature and character of the invention as it is claimed. The accompanying drawings are included to provide a further understanding of the invention, and are incorporated in and constitute a part of this specification. The drawings illustrate various embodiments of the invention, and together with the description serve to explain the principles and operation of the invention.

Brief Description of the Drawings

Fig. 1 is a refractive index profile of an optical waveguide fiber in accord with the invention.

Fig. 2 is a refractive index profile of an optical waveguide fiber in accord with the invention.

Fig. 3 is a refractive index profile of an optical waveguide fiber in accord with the invention.

Fig. 4 is a refractive index profile of an optical waveguide fiber in accord with the invention.

Fig. 5 is an illustration of a span of optical waveguide fiber including the compensating waveguide fiber in accord with the invention.

Fig. 6 is an illustration of a span of optical waveguide fiber including the compensating waveguide fiber in accord with the invention.

Fig. 7 is a refractive index profile of an optical waveguide fiber manufactured in accord with the invention.

Fig. 8 is a chart of total dispersion versus wavelength for the manufactured optical waveguide fiber of Fig. 7.

Fig. 9 is an illustrative chart of a dispersion compensated link in accord with the invention.

Fig. 10 is a refractive index profile of an optical waveguide fiber manufactured in accord with the invention.

Detailed Description of the Invention

Reference will now be made in detail to the present preferred embodiments of the invention, examples of which are illustrated in the accompanying drawings. An exemplary embodiment of the total dispersion and total dispersion slope compensating optical waveguide fiber of the present invention is shown in Figure 1. The segmented core includes a central segment 4 having centerline refractive index depression 2, a first annular segment 6, and a second annular segment 8. The clad layer 10 surrounds the second annular core segment. Dotted line 12 indicates an optional clad layer having a relative index higher than that of adjacent clad layer 10.

The centerline depression 2 is shown for completeness. This depression is typically due to diffusion of dopant material out of the central core segment during preform processing. The depression 2 can be removed by appropriate doping of the central segment centerline. However, the depression is easily included in the model used to calculate the electric field propagating in the fiber so that such appropriate doping of the centerline in actual waveguide fiber manufacture is not required. By including the depression 2 in the model, manufacturing steps needed to make a refractive index profile in accord with the model are simplified. The manufacturing process is stable enough that significant differences in depression 2 do not occur among waveguide fibers drawn from different preforms, when the preforms are made using the same deposition protocol. Preform deposition can be carried out using any of the methods known in the art, including outside vapor deposition, inside vapor deposition, or axial vapor deposition.

The radius of the central segment 4 is shown as radius 14 drawn from the waveguide fiber centerline to the point of intersection of the extrapolated descending portion of segment 4 with the horizontal axis. Radius 16 of first annular segment 6 is drawn from the centerline to the point at which the relative index of segment 6 begins to increase, i.e., intersects the ascending portion of second annular segment 8. Radius 18 of second annular segment 8 is the point at which the descending leg of segment 8 reaches the relative index percent of clad layer 10, i.e., intersects clad layer 10. Radius 20 of clad layer 10 is drawn from the center line to the point at which the relative index begins to increase, i.e, the point of intersection of clad layer 10 and clad layer 12. The radius of clad layer 12 (not shown) extends from the centerline to the point at which the light power propagating in the waveguide fiber is less than about 1% of the peak power. It is known in the art that for the profiles disclosed and described herein, the radius of segment 12 need be no greater than 40 μm and typically is no greater than 35 μm.

The segments of the embodiments of Figs. 2-4, 7 and 10 are similar to the embodiment of Fig. 1 and numbered the same as Fig. 1. The radii of Figs.

2-4, 7, and 10 are also defined in accord with Fig. 1 and are not shown in Figs. 2-4, 7, and 10.

Optical waveguide fibers made in accord with the invention and exemplified in Figs. 1-4, 7, and 10 exhibit the properties desired for compensating total dispersion and total dispersion slope in a high performance system, for example in a system using larger effective area optical waveguide fiber. These properties are:

zero dispersion wavelength λ_o from 1480 nm to 1520 nm (although, depending upon selection of the operating wavelength band, higher values of λ_o can be acceptable);

total dispersion slope at 1550 nm S_t from -1.5 ps/nm^2-km to -4.0 ps/nm^2-km;

total dispersion to S_t ratio from 40 nm to 60 nm;

mode field diameter not less than 4.5 μm;

attenuation at 1550 nm not greater than 0.60 dB/km; and ,

cabled cut off wavelength (for both LP_{11} and LP_{02}) not greater than 1525 nm.

Example 1

A total dispersion and total dispersion compensating optical waveguide fiber was modeled in accord with Fig. 1. The respective relative refractive index percents and radii are:

- central segment 4 relative index 1.76 %;
- radius 14 of central segment 2.19 μm;
- first annular segment 6 relative index -0.4%;
- radius 16 of first annular segment 6.25 μm;
- second annular segment 8 relative index 0.20%; and,
- radius 18 of second annular segment 11.56 μm.

In this first model calculation, the relative refractive index of the second clad layer is zero.

The properties calculated are:

zero dispersion wavelength λ_o 1499.5 nm;

total dispersion slope at 1550 nm S_t -3.59 ps /nm^2-km;

total dispersion to S_t ratio 50.5 nm;

mode field diameter 4.8 μm;

attenuation at 1550 nm 0.25 dB/km; and,

cut off wavelength of LP_{11} 2260 nm and of LP_{02} 1696 nm.

Comparison 1

The profile of example 1 was again modeled with the only change being:

relative index of segment 12 $\Delta_{c2}\%$ is 0.05%; and,

radius 20 of first clad layer is 30 μm.

In this comparison model, all optical waveguide fiber properties are the same except cut off wavelength of LP_{11} is 1352 nm and of LP_{02} is 1488 nm. The function of the relative index difference between the first and second clad layer is to lower cut off wavelength.

Example 2

A total dispersion and total dispersion compensating optical waveguide fiber was modeled in accord with Fig. 2. The respective relative refractive index percents and radii are:

- central segment 4 relative index 1.76 %;
- radius 14 of central segment 2.19 μm;
- first annular segment 6 relative index -0.4%;
- radius 16 of first annular segment 6.25 μm;
- second annular segment 8 relative index 0.30%; and,
- radius 18 of second annular segment 10.00 μm.

In this model calculation, the relative refractive index of the second clad layer is zero.

The properties calculated are:

zero dispersion wavelength λ_o 1500 nm;

total dispersion slope at 1550 nm S_t -3.55 ps /nm^2-km;

total dispersion to S_t ratio 50 nm;

mode field diameter 4.8 μm;

attenuation at 1550 nm 0.25 dB/km; and ,

cut off wavelength of LP_{11} 2108 nm and of LP_{02} 1692 nm.

Comparison 2

The profile of example 2 was again modeled with the only change being:

relative index of segment 12 $\Delta_{c2}\%$ is 0.06%; and,

radius 20 of first clad layer is 30 μm.

In this comparison model, all optical waveguide fiber properties are the same except cut off wavelength of LP_{11} is 1405 nm and of LP_{02} is 1512 nm.

Example 3

A total dispersion and total dispersion compensating optical waveguide fiber was modeled in accord with Fig. 3. The respective relative refractive index percents and radii are:

- central segment 4 relative index 1.76 %;
- radius 14 of central segment 2.19 μm;
- first annular segment 6 relative index -0.4%;
- radius 16 of first annular segment 7.03 μm;
- second annular segment 8 relative index 0.50%; and,
- radius 18 of second annular segment 9.06 μm.

In this model, the relative refractive index of the second clad layer is zero.

The properties calculated are:

zero dispersion wavelength λ_o 1500.2 nm;

total dispersion slope at 1550 nm S_t -3.80 ps /nm^2-km;

total dispersion to S_t ratio 49.9 nm;

mode field diameter 4.8 μm;

attenuation at 1550 nm 0.25 dB/km; and ,

cut off wavelength of LP_{11} 2050 nm and of LP_{02} 1692 nm.

Comparison 3

The profile of example 3 was again modeled with the only change being:

relative index of segment 12 $\Delta_{c2}\%$ is 0.065%; and,

radius 20 of first clad layer is 30 μm.

In this comparison model, all optical waveguide fiber properties are the same except cut off wavelength is of LP_{11} 1425 nm and of LP_{02} 1513 nm.

Example 4

A total dispersion and total dispersion compensating optical waveguide fiber was modeled in accord with Fig. 4. The respective relative refractive index percents and radii are:

- central segment 4 relative index 1.76 %;
- radius 14 of central segment 2.03 μm;
- first annular segment 6 relative index -0.4%;
- radius 16 of first annular segment 7.5 μm;
- second annular segment 8 relative index 0.80%; and,
- radius 18 of second annular segment 9.69 μm.

In this model, the relative refractive index of the second clad layer is zero.

The properties calculated are:

zero dispersion wavelength λ_o 1500.3 nm;

total dispersion slope at 1550 nm S_t -3.97 ps /nm^2-km;

total dispersion to S_t ratio 49.7 nm;

mode field diameter 4.8 μm;

attenuation at 1550 nm 0.25 dB/km; and ,

cut off wavelength of LP_{11} is 2021 nm and of LP_{02} is 1692 nm.

Comparison 4

The profile of example 4 was again modeled with the only change being:

relative index of segment 12 Δ_{c2}% is 0.067%; and,

radius 20 of first clad layer is 30 μm.

In this comparison model, all optical waveguide fiber properties are the same except cut off wavelength of LP_{11} 1447 is nm and of LP_{02} is 1523 nm.

In each of examples 1-4 the pin array bend loss was not greater than 57 and effective area had a range from 18. 3 to 19 μm^2. The ratio of total dispersion to total dispersion slope for Corning LEAF ® Fiber is about 50. The optical waveguide fiber made in accord with the invention is therefore well suited to being a total dispersion and total dispersion compensating waveguide fiber in systems using the LEAF® fiber.

Manufacturing Example 5

A total dispersion and total dispersion compensating optical waveguide fiber was manufactured in accord with Fig. 7. The respective relative refractive index percents and radii are:

- central segment 4 relative index 1.67 %;
- radius 14 of central segment 1.57 μm;
- first annular segment 6 relative index -0.44%;
- radius 16 of first annular segment 6.50 μm;
- second annular segment 8 relative index 0.20% (near the geometric center of the segment); and,
- radius 18 of second annular segment 11.13 μm.

In this manufactured fiber, the relative refractive index of the second clad layer is zero.

The properties were measured to be (See Fig. 8, curve 25 for values of total dispersion and total dispersion slope):

zero dispersion wavelength λ_o 1534 nm;
total dispersion slope at 1550 nm S_t -2.67 ps /nm^2-km;
total dispersion to S_t ratio (at 1550 nm) 56 nm; and,
attenuation at 1550 nm 0.60 dB/km.

Manufacturing Example 6

A total dispersion and total dispersion compensating optical waveguide fiber was manufactured in accord with Fig. 10. The respective relative refractive index percents and radii are:

- central segment 4 relative index 1.45 %;
- radius 14 of central segment 1.5 μm;
- first annular segment 6 relative index -0.35%;
- radius 16 of first annular segment 6.75 μm;
- second annular segment 8 relative index 0.33%; and,
- radius 18 of second annular segment 11.75 μm. The relative refractive index 12 of the second clad layer is 0.08% and the radius 20 of the second clad layer is 30 μm.

The properties measured are:

zero dispersion wavelength λ_o 1496.5 nm;

total dispersion slope at 1550 nm S_t -3.286 ps /nm^2-km;

total dispersion to S_t ratio 50 nm;

mode field diameter 5.5 μm;

attenuation at 1550 nm 0.60 dB/km; and,

cut off wavelength of LP_{11} and of LP_{02} was 1738 for a fiber length of 2 meters, 1320 for a fiber length of 1 km, and 1270 for a fiber length of 2 km.

The profiles disclosed and claimed show the advantages of introducing a relative index difference between a first and a second clad layer. The respective cut off wavelengths of the next two higher modes LP_{11} and LP_{02}, above the fundamental mode LP_{01}, can be adjusted without changing the other key parameter of the waveguide fiber.

A compensated span of optical waveguide fiber is illustrated in Fig. 5. A high performance waveguide fiber 22, typically having low attenuation over a pre-selected operating wavelength window, large effective area, and low total dispersion is connected in series arrangement with the compensating optical waveguide fiber 24 made in accord with the invention. The dotted line connecting waveguide fibers 22 and 24 indicates that the length of the span is a variable to be selected. The span terminates in optical connections 26 and 28, respectively, which represent input ports for a coupler, a wavelength division multiplexing component, a receiver, or a transmitter. The dotted line also is intended to represent the possibility that components such as optical amplifiers may be incorporated into the span. The choice of components to be included in the span depends upon the desired span performance. The design of a span corresponding to a particular set of performance requirements, such as end to end attenuation, number of multiplexed channels, or channel spacing, is known in the art. The insertion of such components does not in general affect the refractive index profile or the length of the compensating optical waveguide fiber disclosed and described herein. Thus, such components will not be discussed further here.

A sample calculation is made to show how the total dispersion and total dispersion slope compensating fiber length is selected. The calculation set

forth here also shows that adequate compensation over an extended wavelength band is possible even if the respective ratios (total dispersion to total dispersion slope) of fibers 22 and 24 are equal only to within 5 %.

A high performance fiber 22 has total dispersion slope S_{t1} = 0.085 ps/nm^2-km at 1550 nm, ratio 47.5 nm at 1550 nm, and length L_1 = 100 km. Then the end to end dispersion of fiber 22 is 404 ps/nm at 1550 nm, 489 ps/nm at 1560 nm, and 617 ps/nm at 1575 nm. Compensating waveguide fiber 24 in accord with the invention has total dispersion slope S_{t2} = -3.5 ps/nm^2-km at 1550 nm, ratio 50 (differs from that of fiber 22 by 5%) at 1550 nm, and a length L_2 selected to completely compensate the span at 1550 nm. Given these values, the length of the compensating waveguide fiber is found as L_2 = (404 ps/nm)/(3.5 ps/nm^2-km) = 2.31 km. The amount of dispersion compensation provided by this particular waveguide fiber in accord with the invention at 1560 nm is 484 ps/nm and at 1575 nm is 606 ps/nm. Thus at 1575 nm the compensating optical waveguide fiber compensates the span to within 2% of zero, i.e., perfect compensation.

Fig. 6 is an alternative embodiment of the compensated span in accord with the invention. In this embodiment, the compensating fiber 24, which typically has lower effective area than high performance fiber 22, is connected in series arrangement with fibers 22 at either end. In this configuration, the span can be more effectively used for bi-directional transmission of optical signals. That is, the signal intensity is larger at points nearer the transmitter. By optically connecting fibers 22 to the transmitters at each end of the span, the highest intensity signal travels in the highest effective area optical waveguide fiber, thereby limiting non-linear dispersion effects.

System Example 7

A compensated system in accord with the invention having 100 km of Corning LEAF® and 2.5 km of the negative total dispersion and negative total dispersion slope in accord with the invention was modeled. The results of the model are shown in Fig. 9. The total dispersion versus wavelength of the 100 km of LEAF® fiber is shown as curve 28. The total dispersion versus wavelength of the compensating waveguide fiber in accord with the invention is

shown as curve 26. Because of the nearly equal ratio of total dispersion to total dispersion slope of the two waveguide types comprising the system, the end to end dispersion of the system, shown as curve 30 in Fig. 9 varies less that 60 ps over the wavelength range from 1480 nm to 1620 nm. Over the more limited range from about 1550 nm to 1620 nm, the compensation is nearly ideal, that is, there is essentially no variation in the compensation as wavelength changes.

It will be apparent to those skilled in the art that various modifications and variations of the present invention can be made without departing from the spirit and scope of the invention. Thus, it is intended that the present invention include the modifications and variations of this invention provided they come within the scope of the appended claims and their equivalents.